AF Spin Gap Limits the Coherent SC Gap in Cuprates

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BROOKHAVEN NATIONAL LABORATORY

Correlated Electron Systems — Novel Developments
William I. Fine Theoretical Physics Institute
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U.S. DEPARTMENT OF ENERGY | Office of Science

CES center for emergent superconductivity

Outline

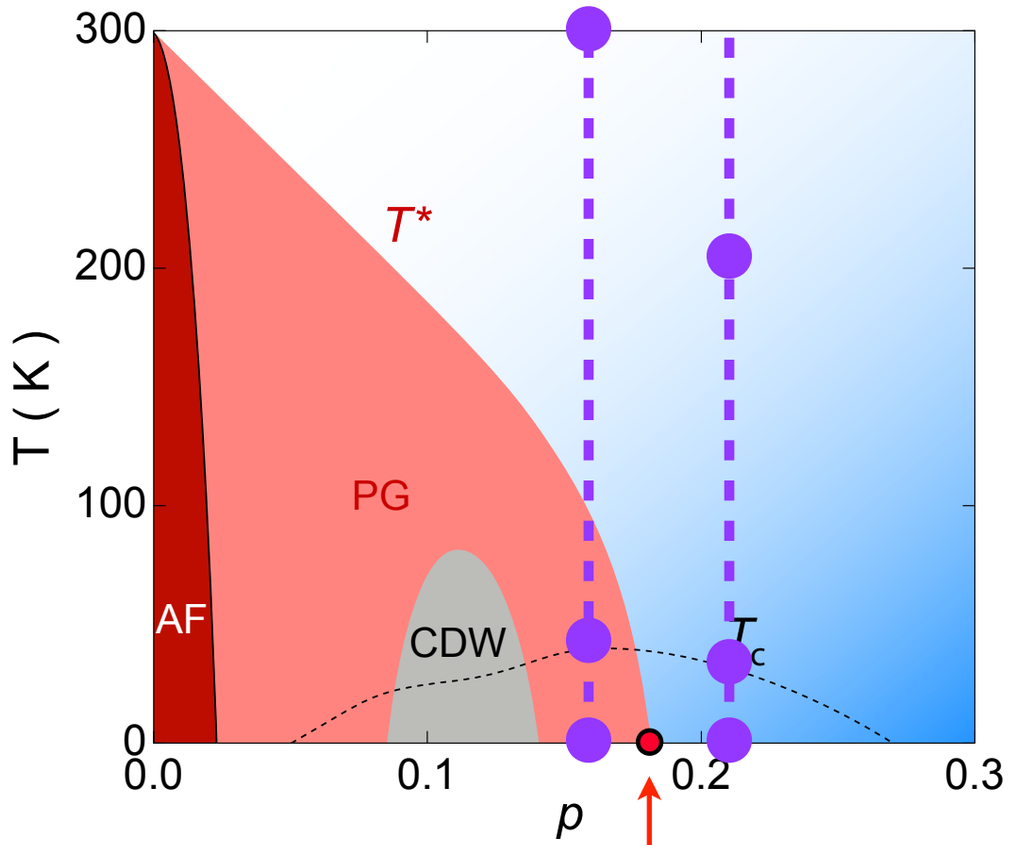
- Motivation
- Measure spin fluctuations in $La_{2-x}Sr_xCuO_4$ x=0.17, 0.21
  - SC spin gap where spectral weight is low
- Coherent superconducting gap, Δ_c, from Raman B_{2g}
- Observation: $\Delta_c \leq \Delta_{spin}$
- Implications

Collaborators

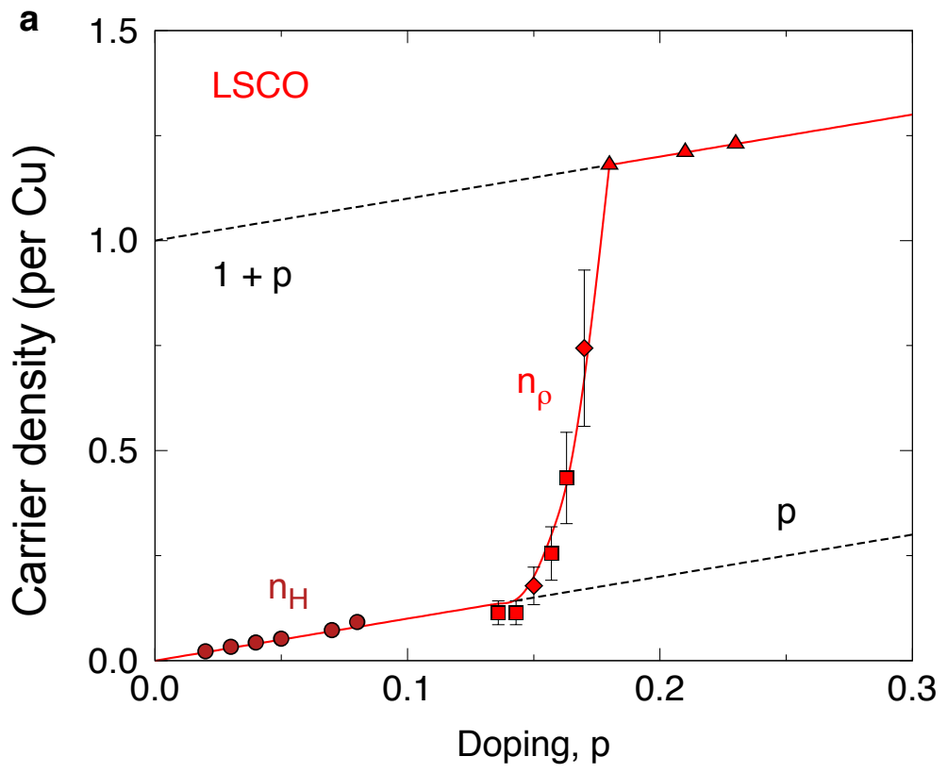
Brookhaven
- Yangmu Li
- *Ruidan Zhong* → Princeton
- Genda Gu
- Igor Zaliznyak

ORNL
- Matt Stone
- Sasha Kolesnikov

Following Spin Fluctuations across the Pseudogap



Laliberte *et al.*, arXiv:1606.04491



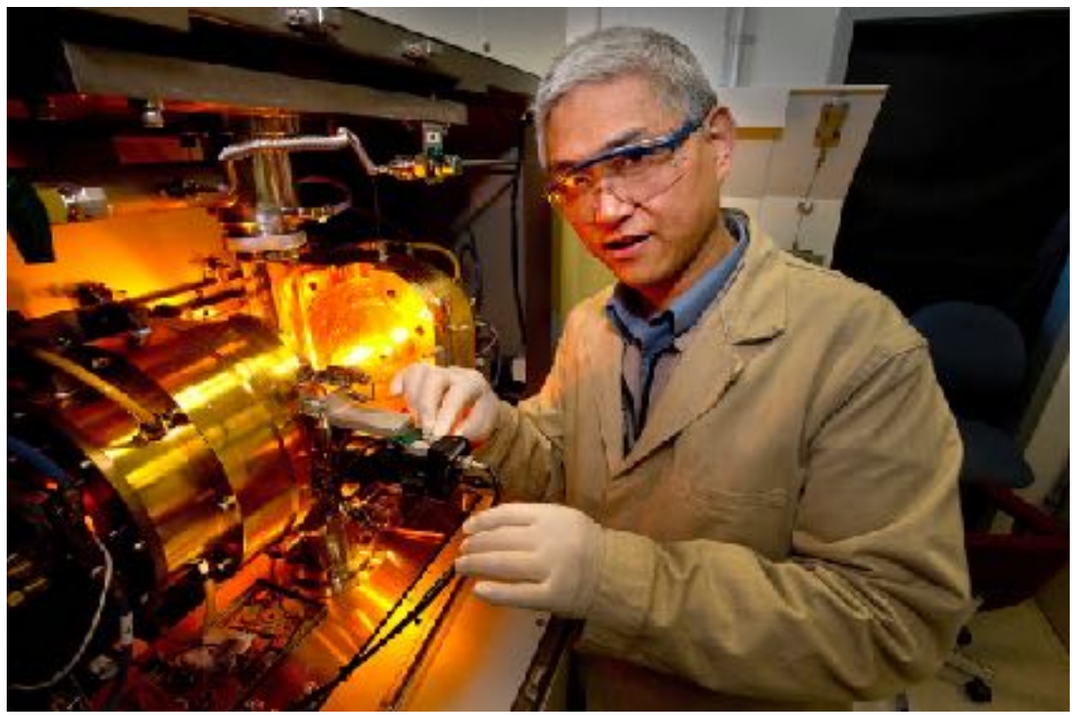
crossover from Fermi arcs/pockets to full Fermi surface

ARPES: H.-B. Yang *et al.*, PRL (2011)
SI-STM: K. Fujita *et al.*, Science (2014)

Quantum critical point or collapse of cooperative correlations?

compare $S(\mathbf{Q},\omega)$ in $La_{2-x}Sr_xCuO_4$ with x = 0.17 and 0.21

Experiments

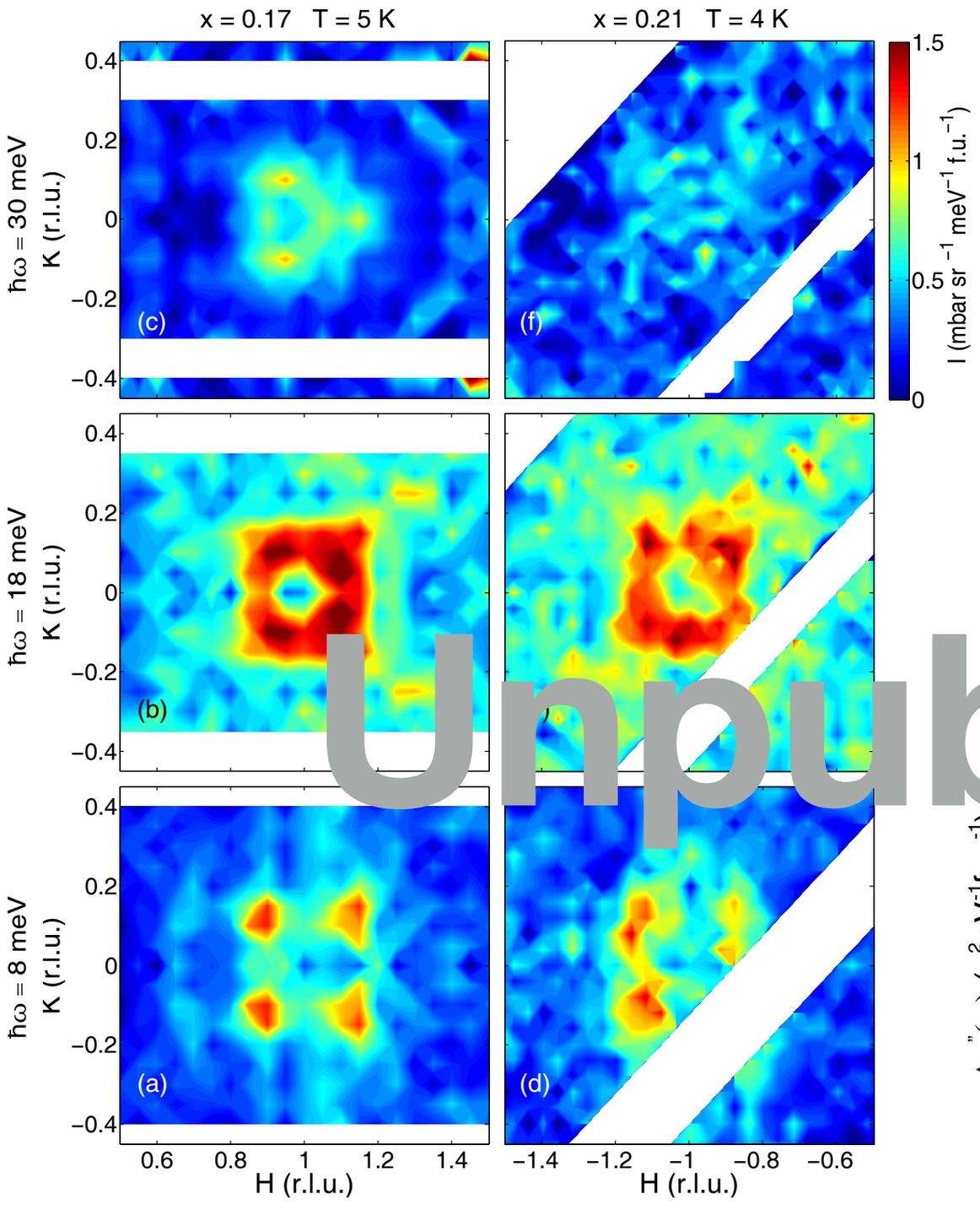


Genda Gu grew LSCO crystals at BNL

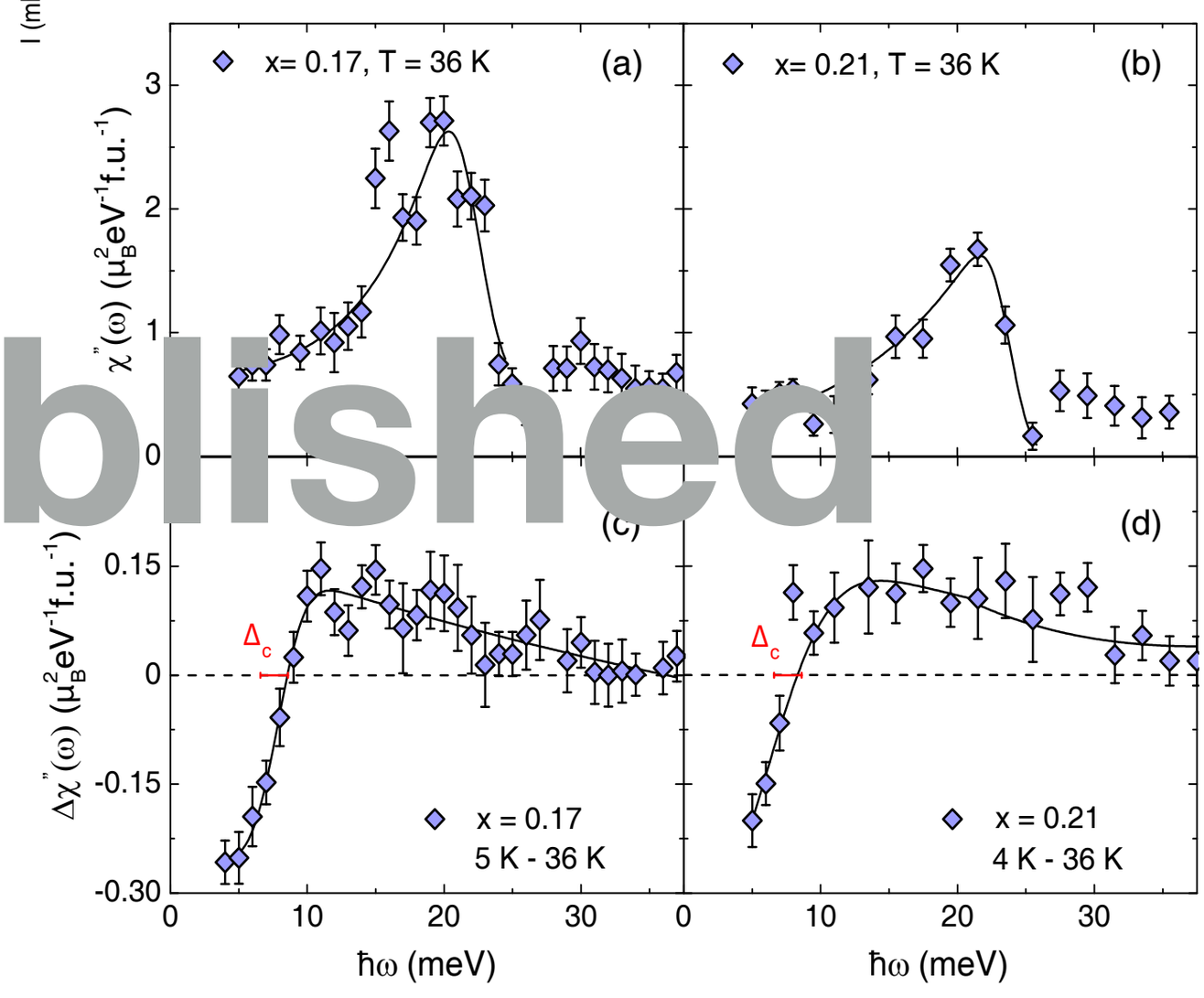
Neutron scattering experiments on SEQUOIA TOF spectrometer
at the Spallation Neutron Source, ORNL

Magnetic scattering in LSCO

x = 0.17 x = 0.21



x = 0.17 x = 0.21



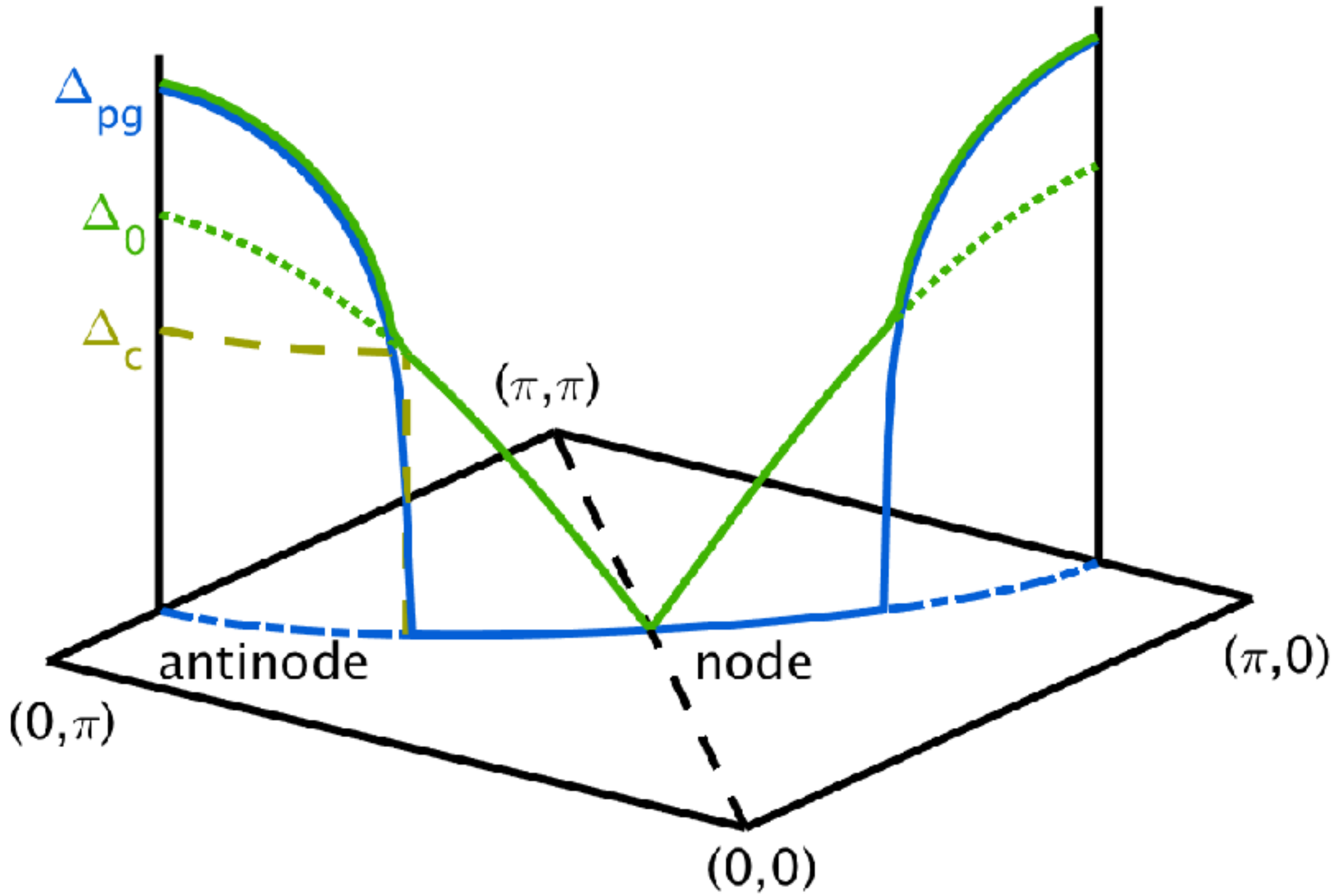
Observations

- Effective spin gap present in normal state
  - Incompatible with critical behavior

- Shift of magnetic spectral weight across T_c is small

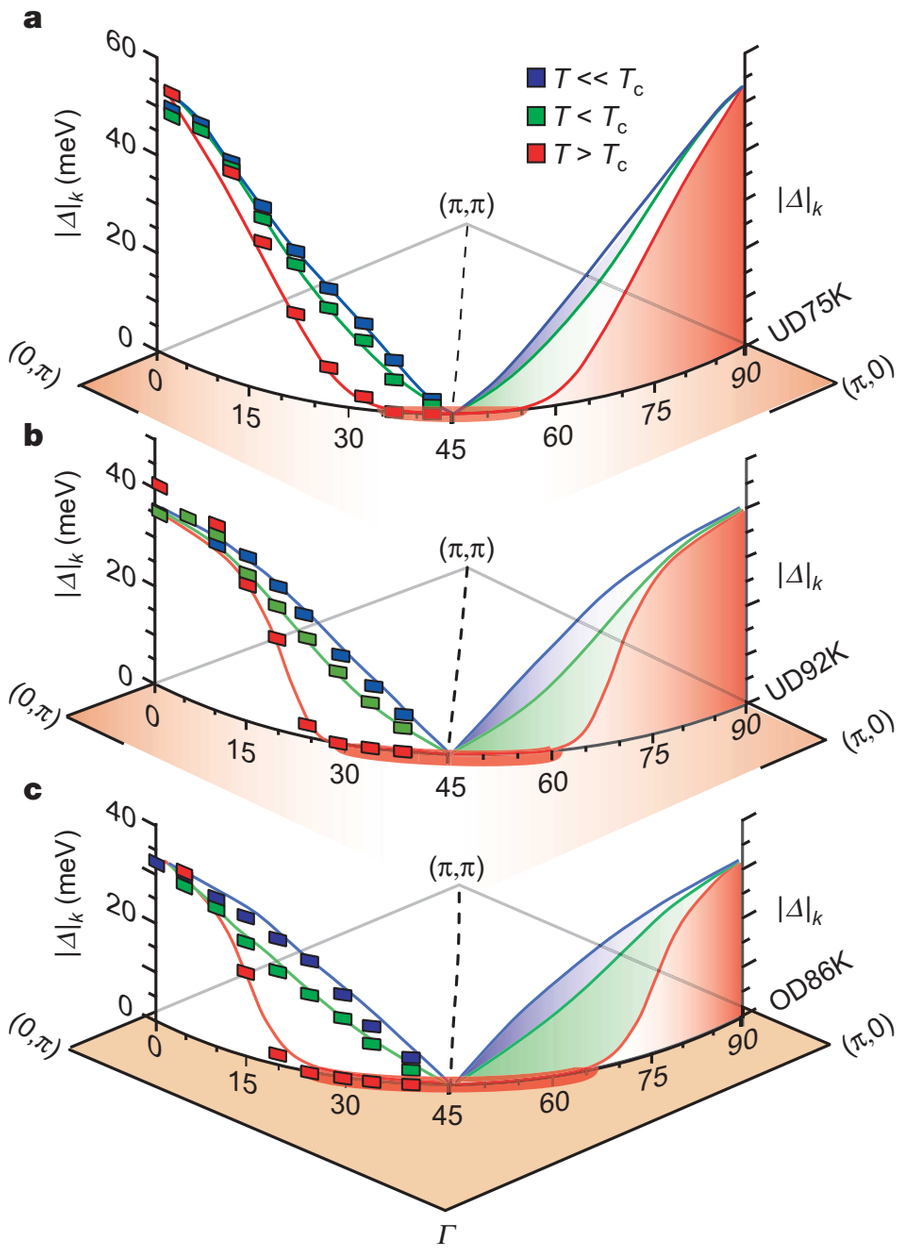
- Could the spin gap limit the SC order?

Various gap scales



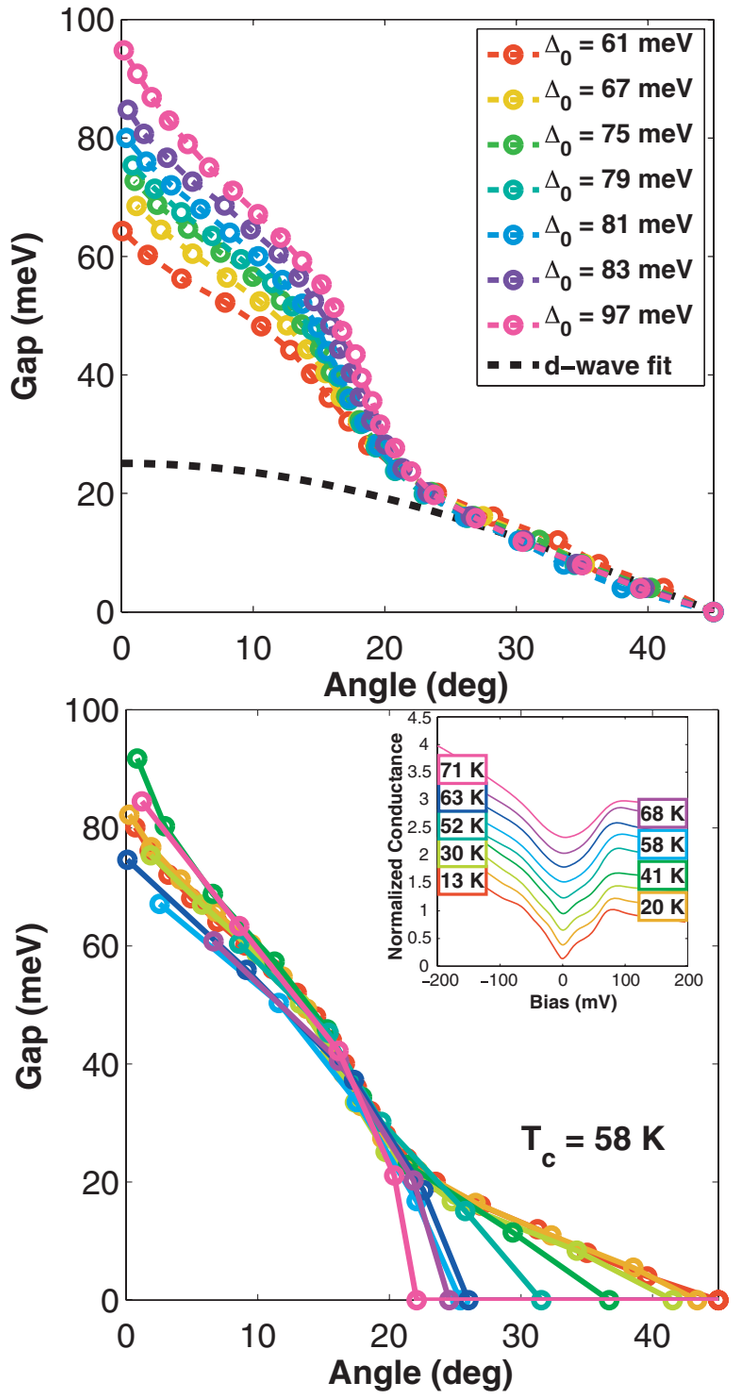
Gap measurements for Bi2212

ARPES results



W.S. Lee *et al*., Nature **450**, 81 (2007)

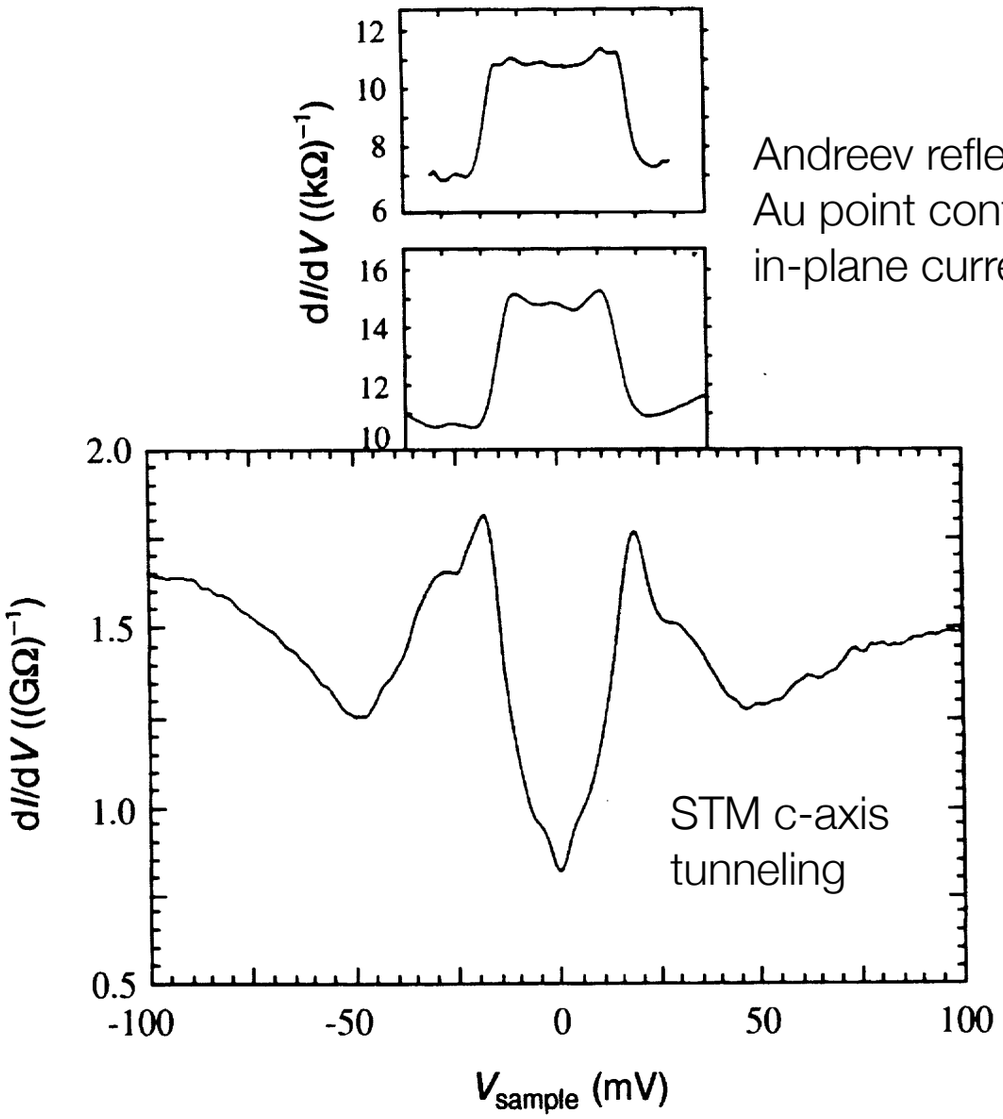
STM results



A. Pushp *et al*., Science **324**, 1689 (2009)

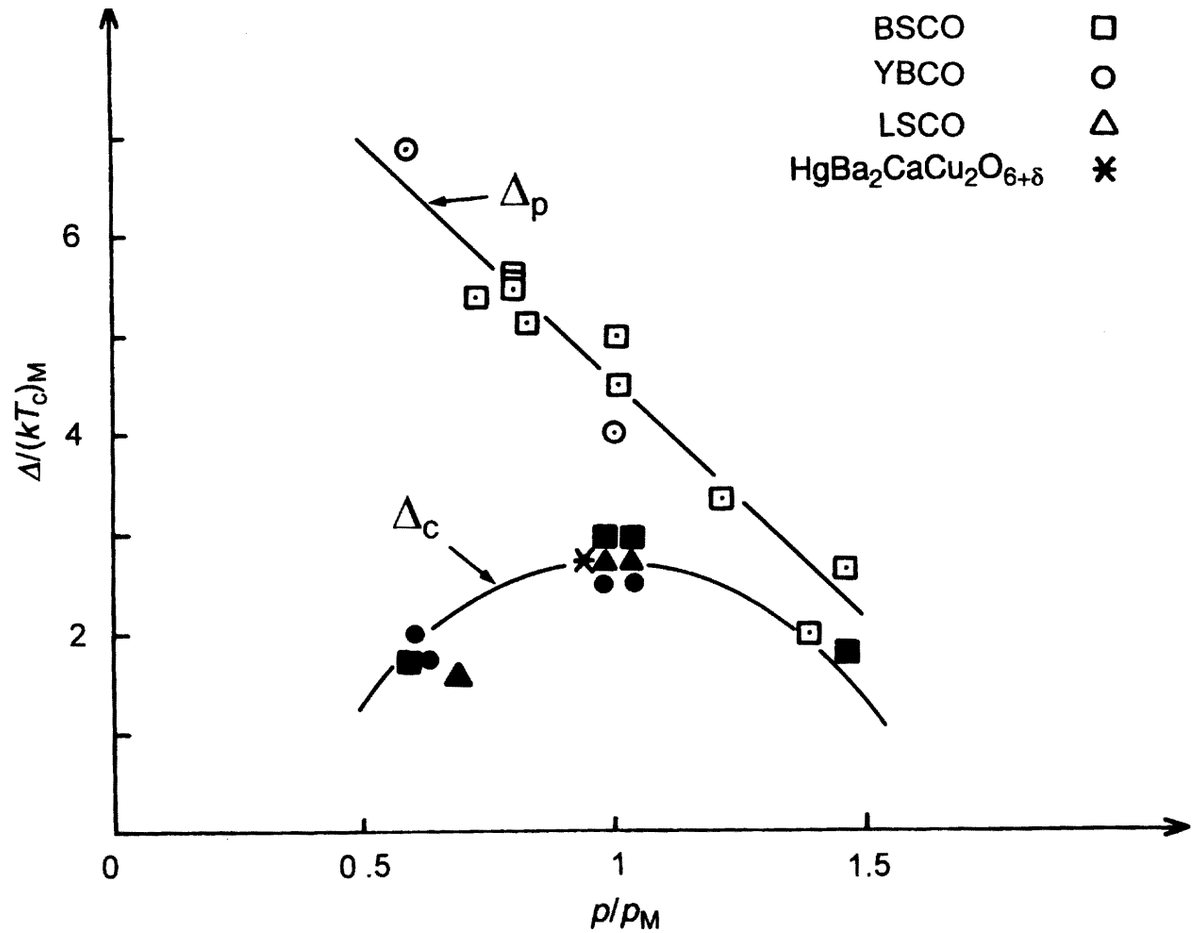
Coherent gap vs. pseudogap

YBCO



Andreev reflection,
Au point contact,
in-plane current

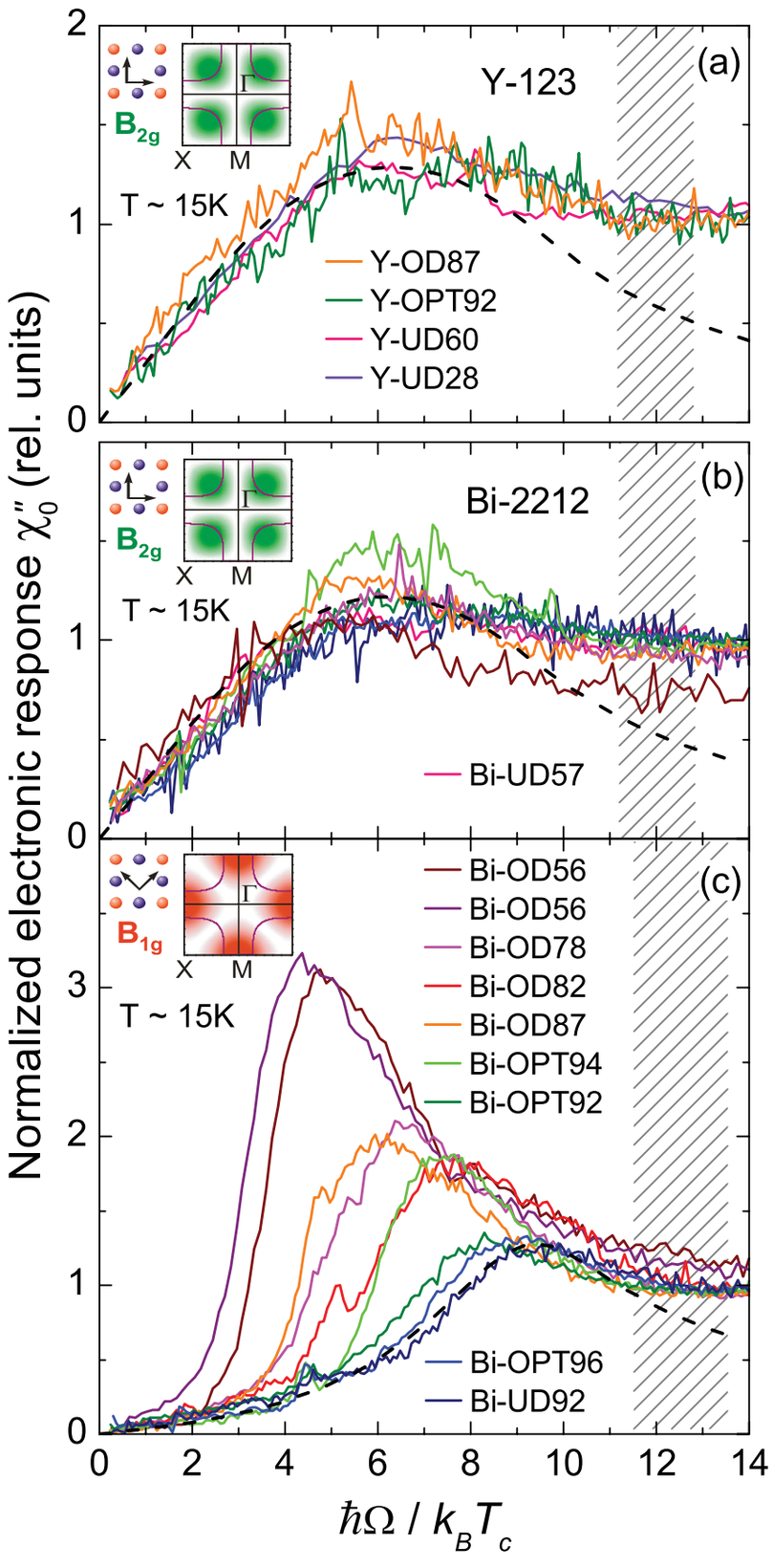
STM c-axis
tunneling

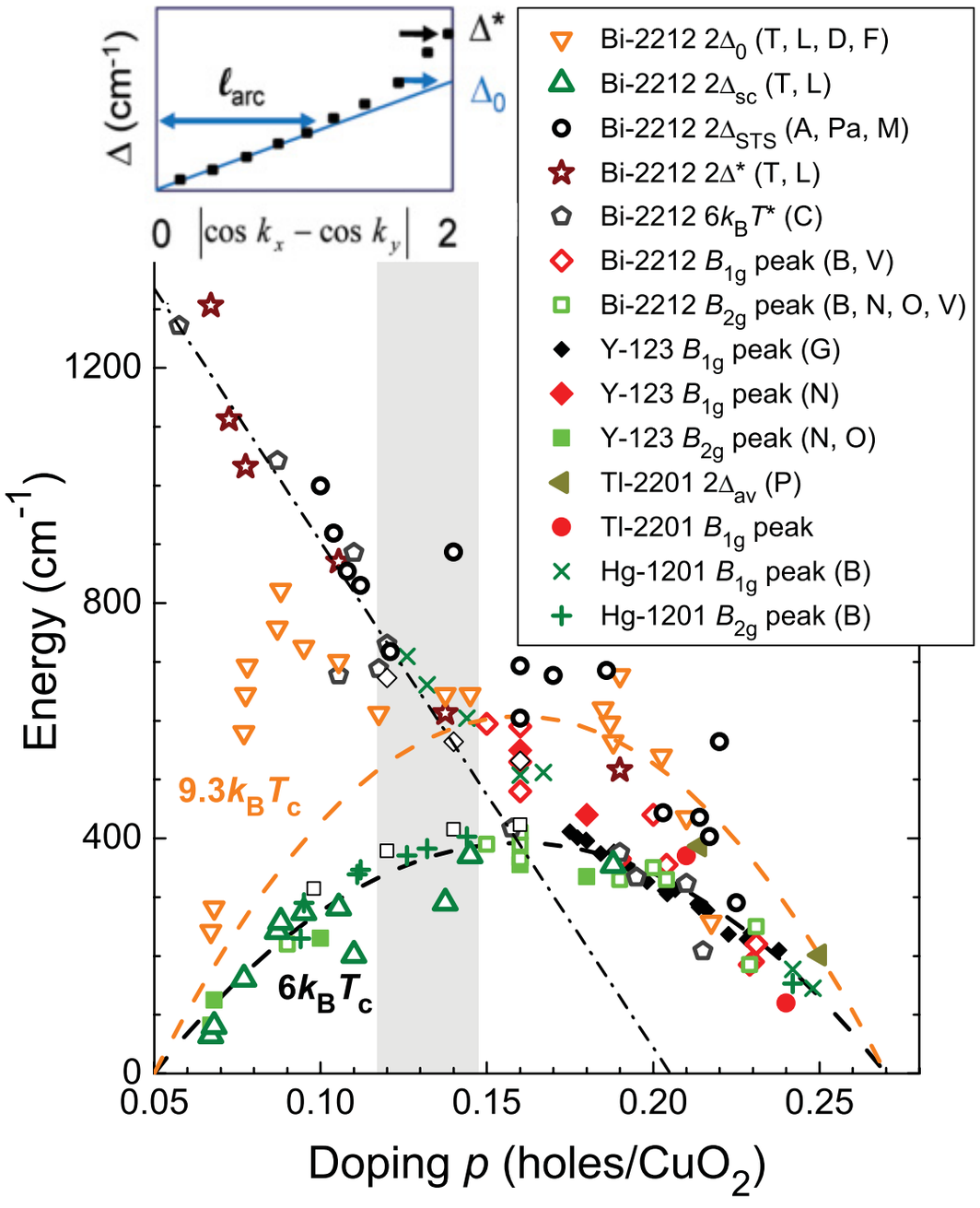


G. Deutscher, Nature **397**, 410 (1999)

Raman scattering with B_{2g} symmetry

$$\hbar\Omega_{peak}(B_{2g}) = 2\Delta_c = 6kT_c$$

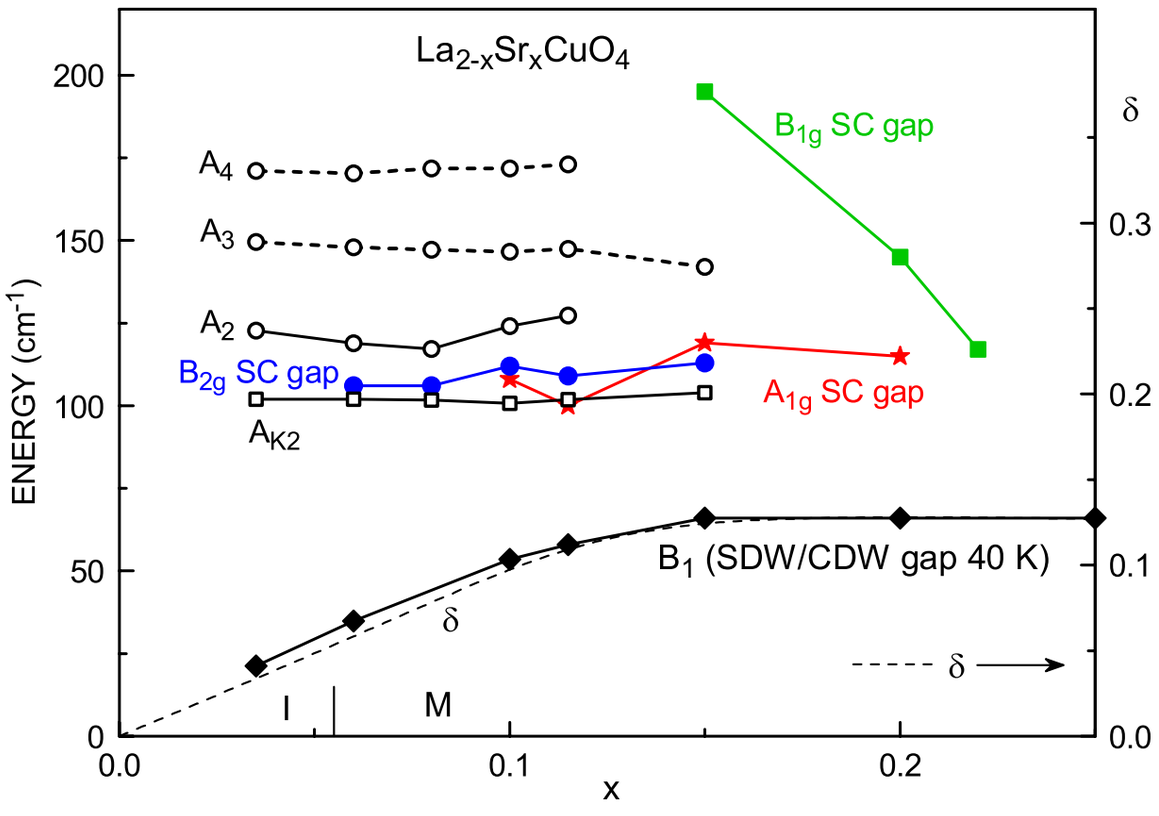




N. Munnikes *et al.*, PRB **84**, 144523 (2011)

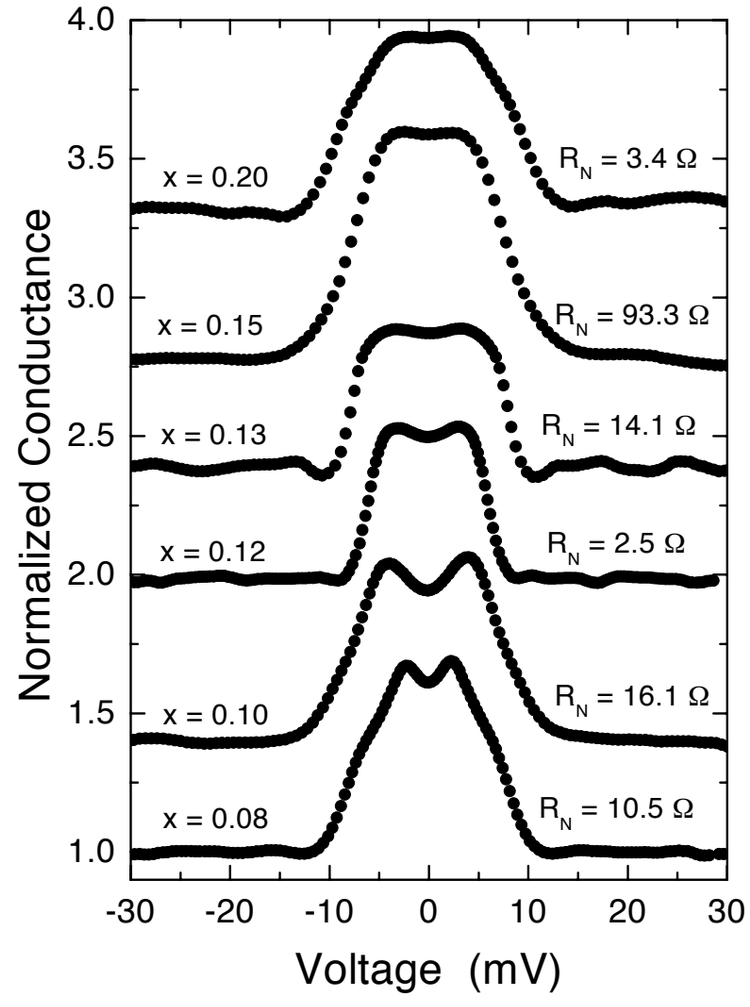
Δ_c for LSCO

Raman scattering



S. Sugai *et al*., J. Phys.: Condens. Matter **25**, 475701 (2013)

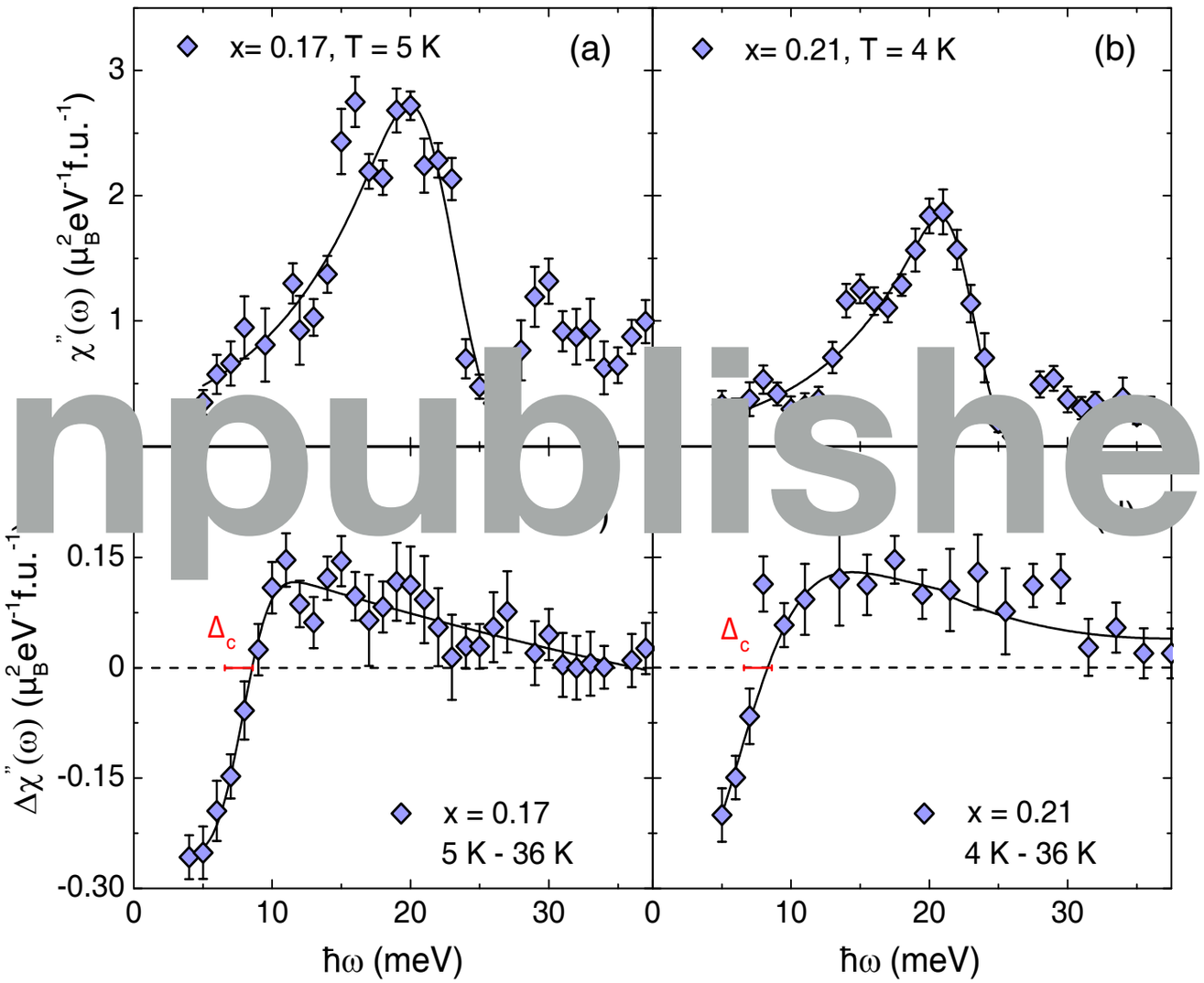
Andreev reflection



R.S. Gonnelli *et al*., EPJB **22**, 411 (2001)

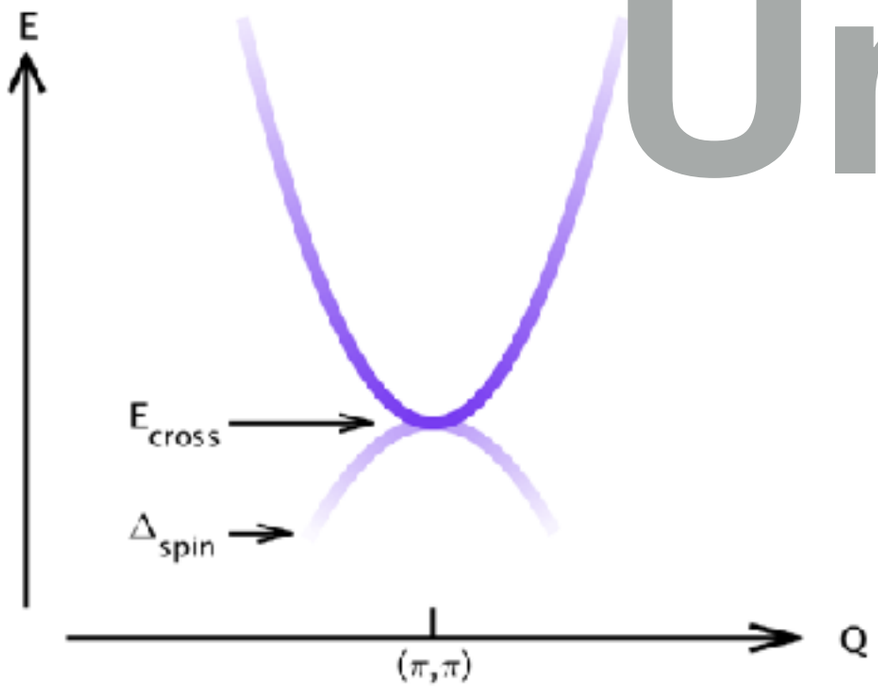
$\Delta_c \approx 8$ meV

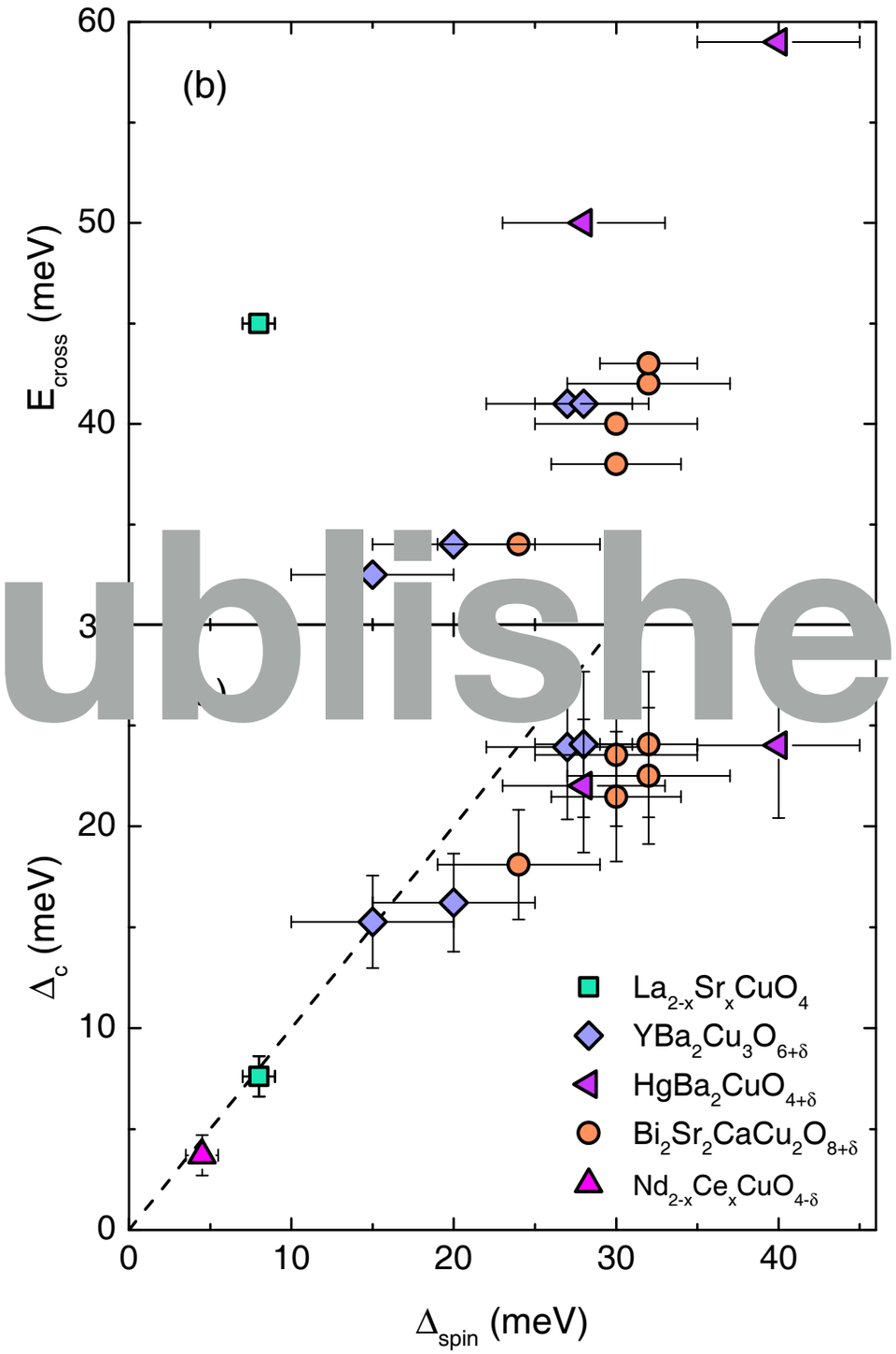
LSCO: $\Delta_c = \Delta_{spin}$



Compare with other cuprates

$\Delta_c \leq \Delta_{spin} < E_{cross}$



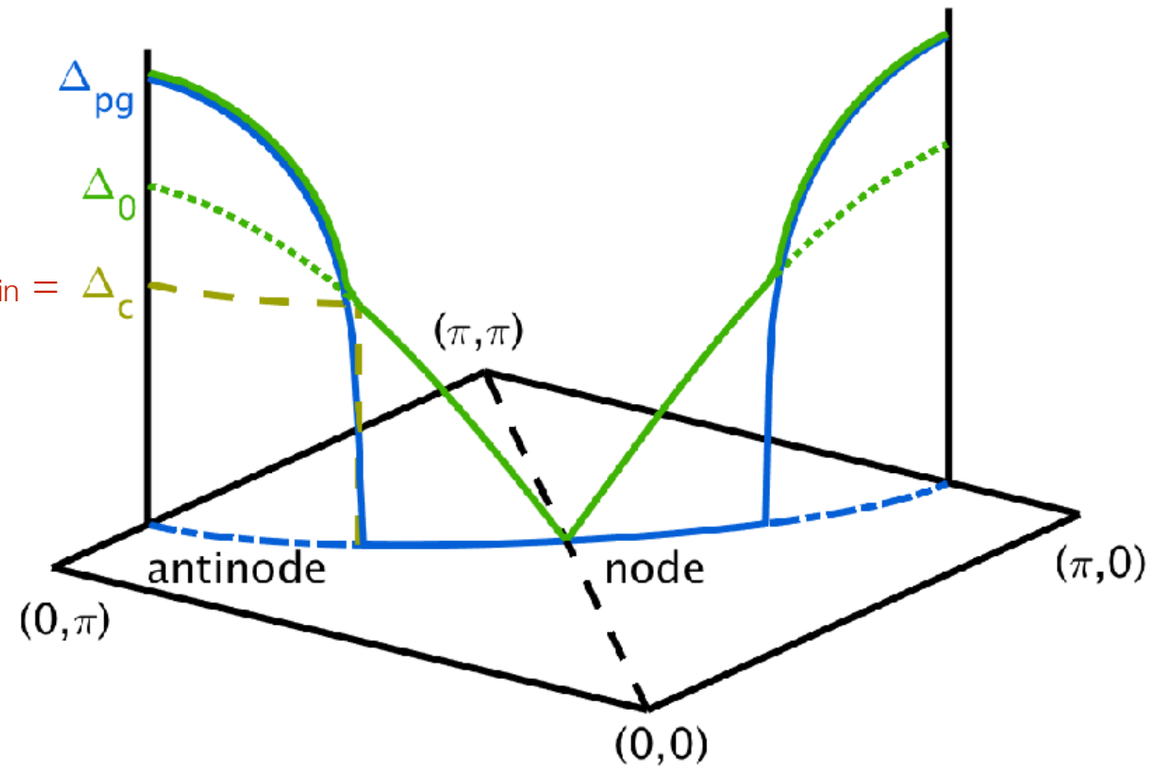


Interpretation

- QPs present in nodal region of uniform d-wave SC

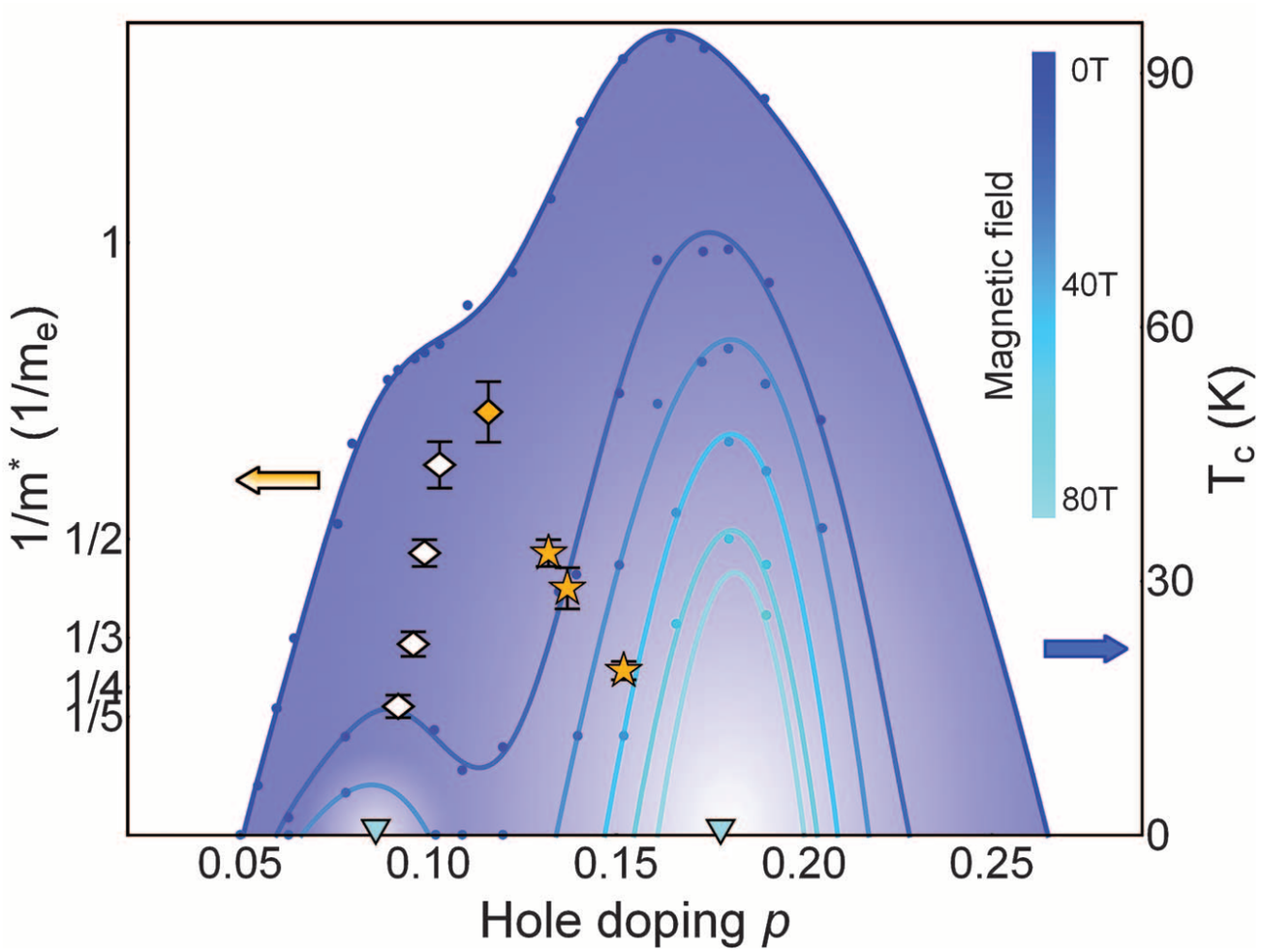
- QPs exist only for $E < \Delta_{spin}$

- Underdamped QPs are not compatible with AF spin fluctuations

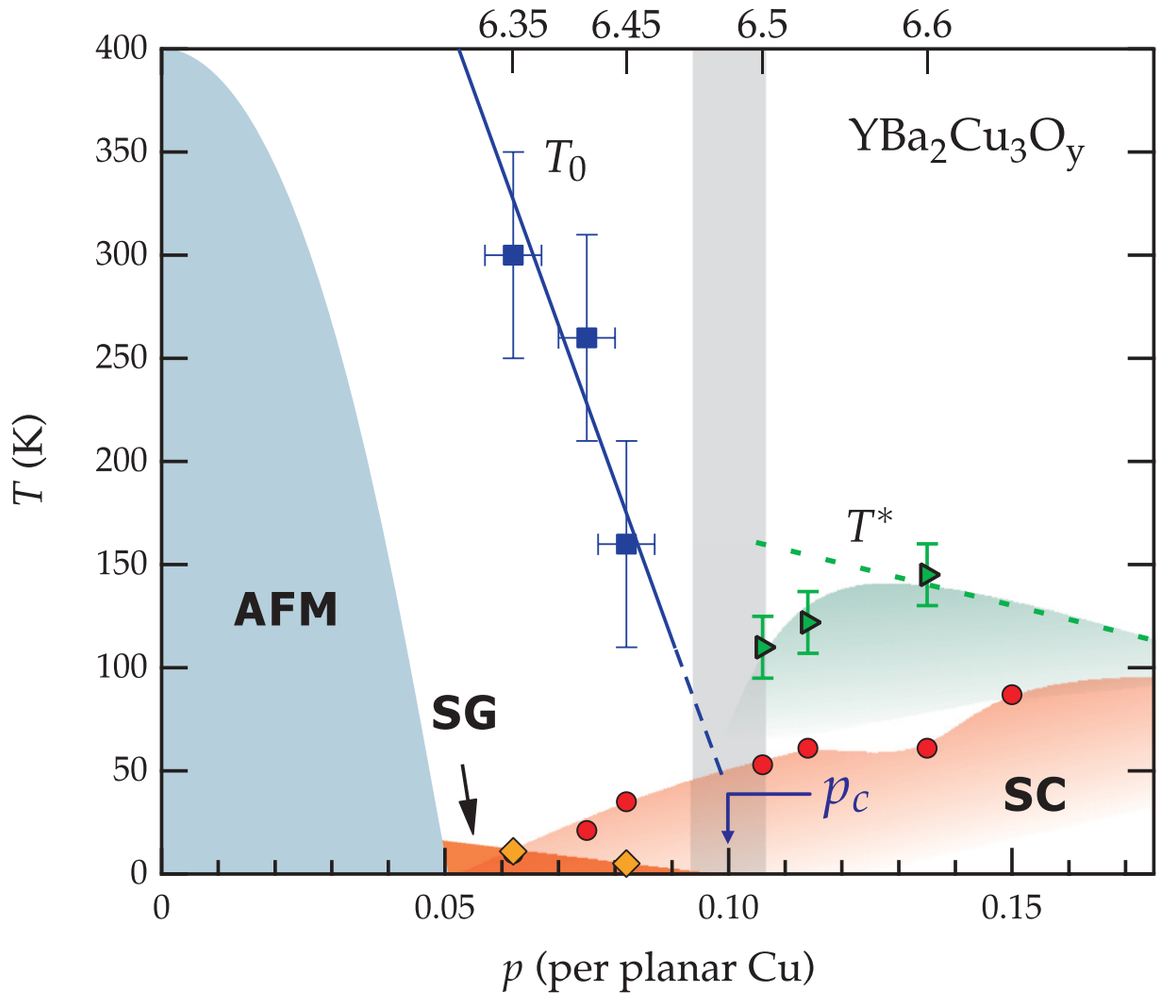


Quantum oscillations in YBCO

Are observed in the doping range where NMR detects a spin gap



B.J. Ramshaw *et al*., Science **348**, 317 (2015)

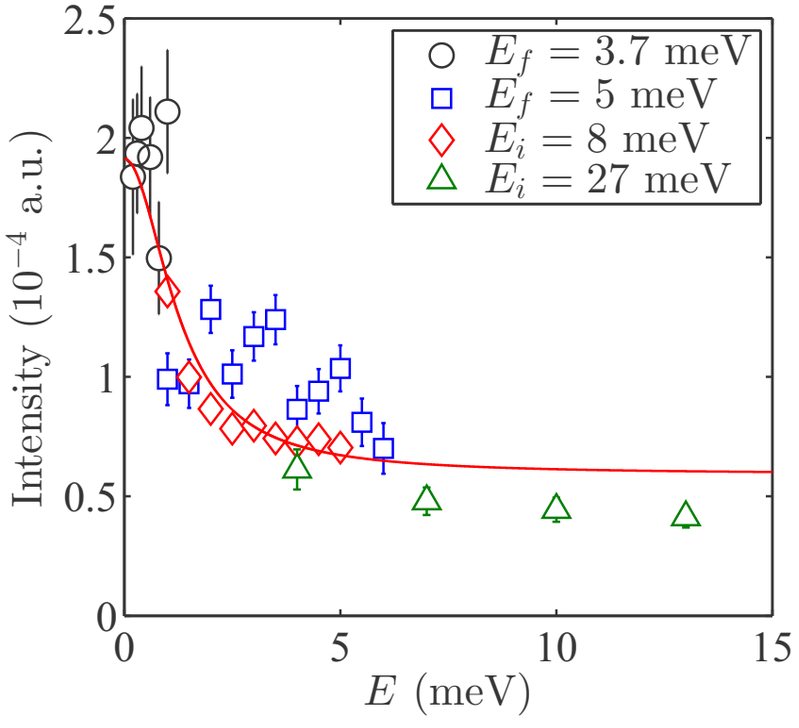


S.-H. Baek *et al*., PRB **86**, 220504(R) (2012)

Overdamped QPs in presence of spin fluctuations

LSCO x = 0.07

magnetic neutron scattering
Q-integrated



No spin gap!

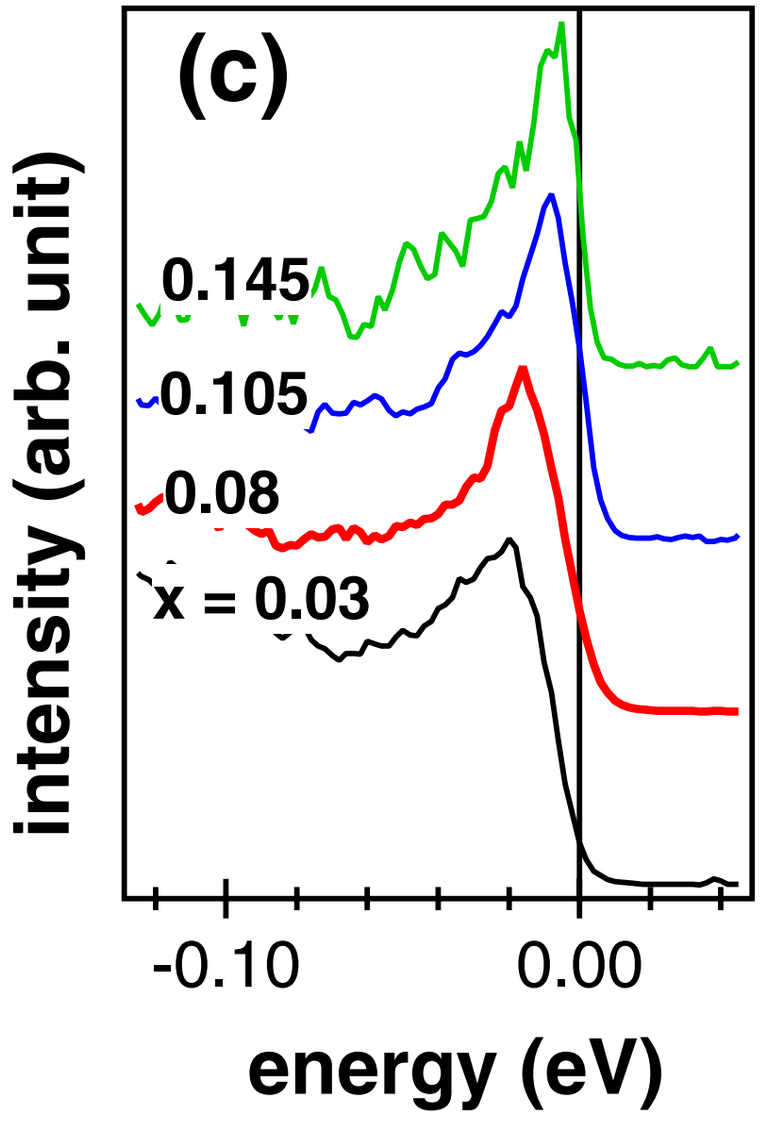
H. Jacobsen *et al*., PRB **92**, 174525 (2015)

ARPES at node

Peak broadens and shifts from E_F when gapless spin fluctuations present

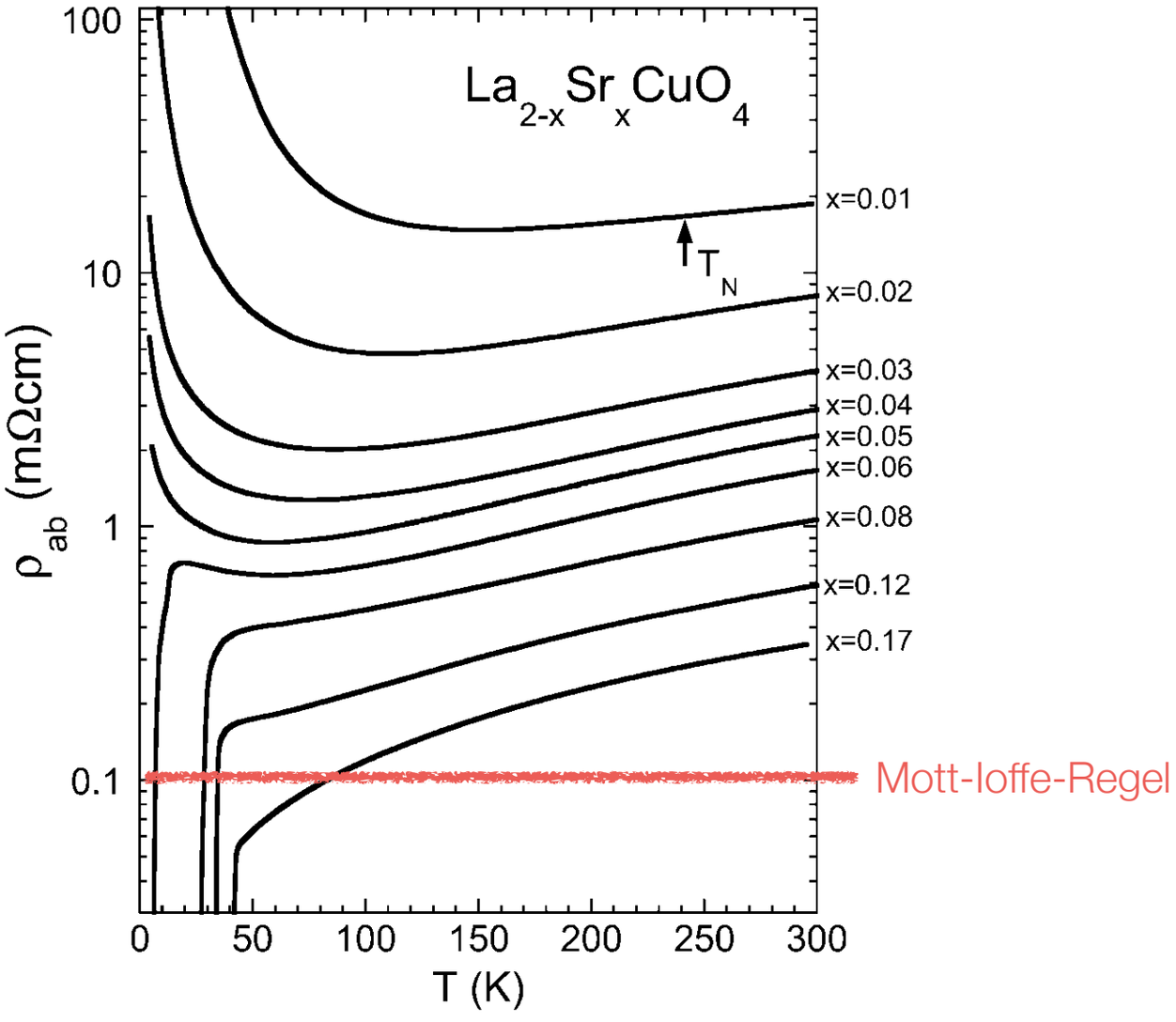
"nodal gap"

LSCO x = 0.08



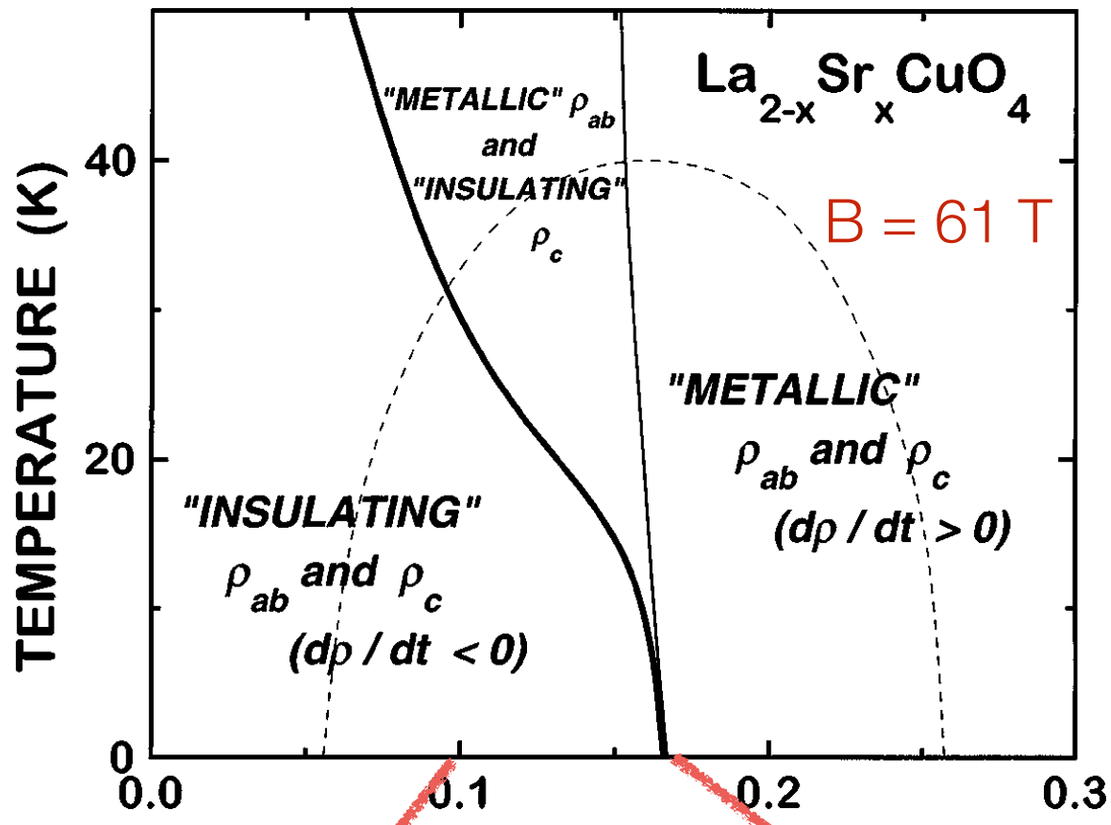
E. Razzoli *et al*., PRL **110**, 047004 (2013)

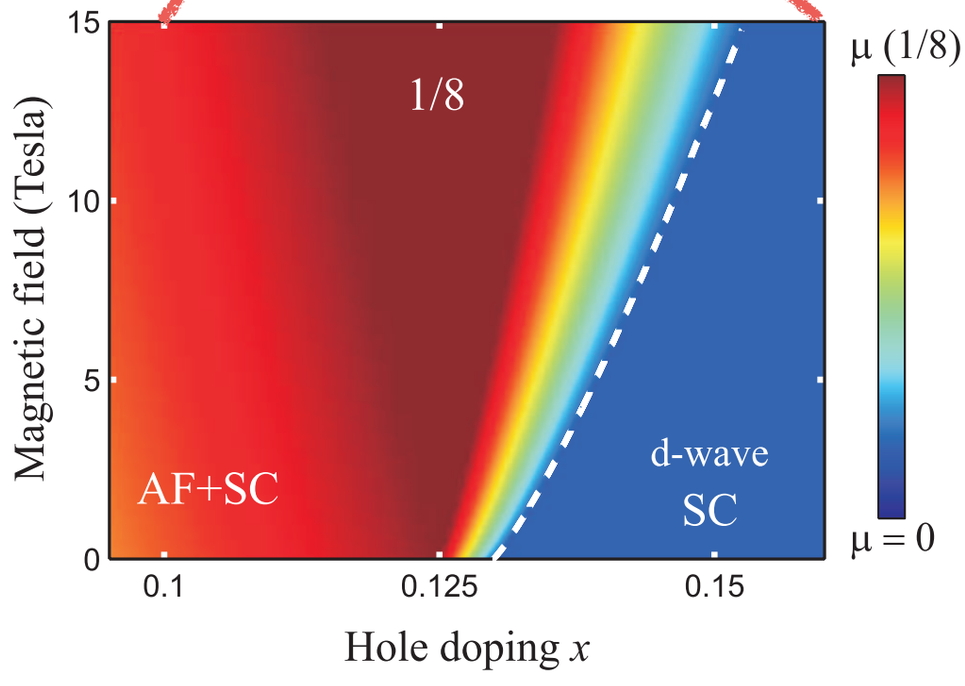
Insulator-to-metal transition correlates with $\Delta_{spin} \rightarrow 0$



Y. Ando *et al*., PRL **87**, 017001 (2001)

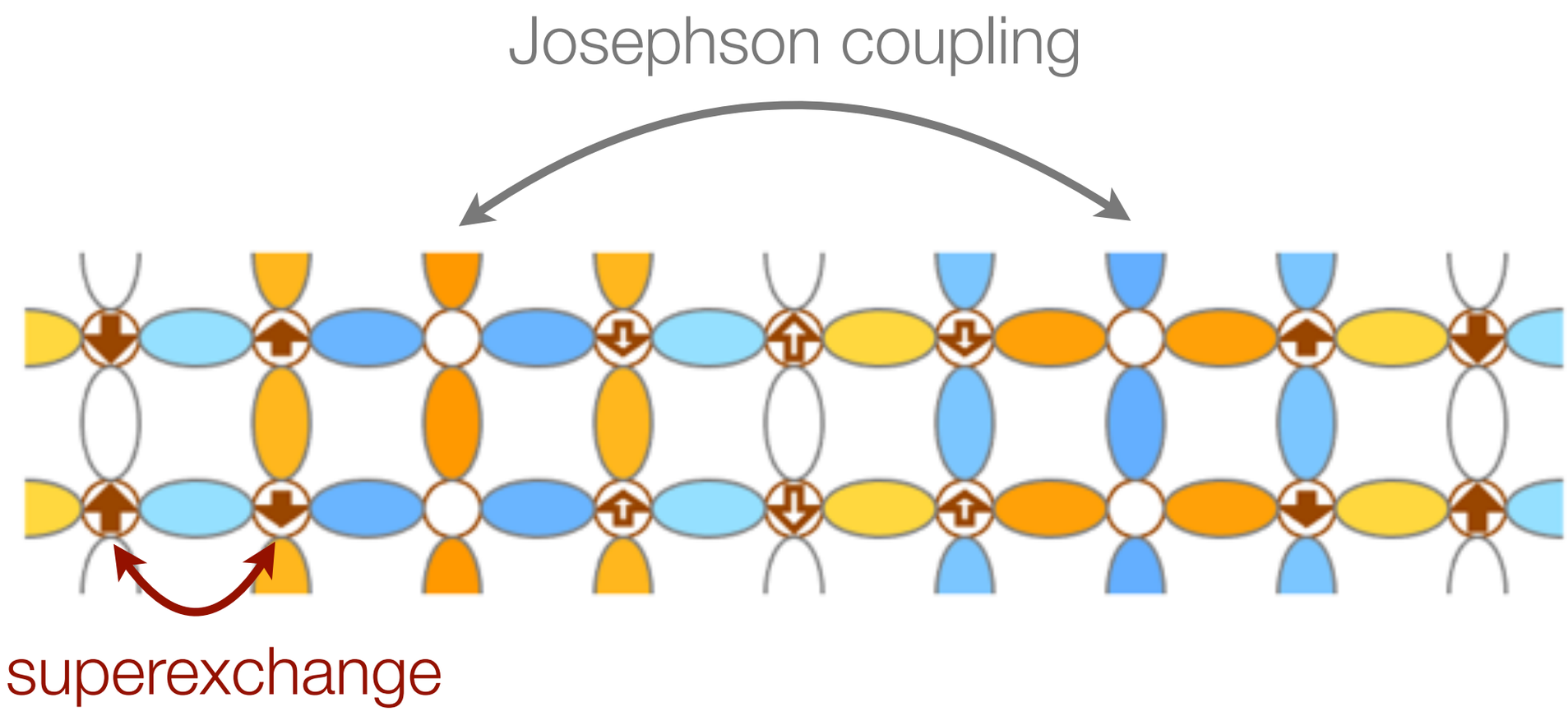
G. Boebinger *et al*., PRL **77**, 5417 (1996)





J. Chang *et al*., PRB **78**, 104525 (2008)

Alternative superconducting state



Pair Density Wave does not require coherent QPs

see: E. Fradkin *et al*., RMP **87**, 457 (2015)

Summary

- Experimental result:
  - $\Delta_c \leq \Delta_{spin}$
- Implications:
  - Putative QCP is not due to AF criticality
  - Coherent QPs do not coexist with local AF spin fluctuations in cuprates